Smart Acoustic Network Using Combined Fsk-Psk, Adaptive Beamforming and Equalization

Steven G. Schock P.I.
Department of Ocean Engineering
Florida Atlantic University – SeaTech
101, North Beach Road, Dania Beach, FL 33004
phone: (561) 297-3442 fax: (561) 297-3885 email: schock@oe.fau.edu

Pierre-Philippe J. Beaujean Co-P.I.
Department of Ocean Engineering
Florida Atlantic University – SeaTech
101, North Beach Road, Dania Beach, FL 33004
phone: (954) 924-7051 fax: (954) 924-7233 email: pbeaujea@seatech.fau.edu

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LONG-TERM GOALS

Our long-term objective is a smart acoustic network for multiple underwater vehicle operation, with integrated communication and positioning capability. To do so, a new generation of Coherent Path Beamformer would act as a network decoder and arbitrator for data communication and long (short) base line. Also, wireless communication to shore would be available for control and real-time data transfer. Finally, the underwater vehicles will be carrying an improved version of the compact low-cost Acoustic Modem. This concept requires the network to be synchronous. The concept is to make the most efficient use of time and frequency band.

OBJECTIVES

The smart acoustic network is a multiple-layer system that achieves distinct tasks. As a result, our research effort has been divided into three main projects:

1. High-speed acoustic communication using a High Performance Acoustic Link (FAU-HPAL, Figure 1), also know as “MillsCross”.
2. High-reliability acoustic network using multiple General Purpose Acoustic Modems (FAU-GPAM, Figure 2), with a monitoring option using the FAU-HPAL.
3. Development of a Dual-Purpose navigation/telemetry Acoustic Modem (FAU-DPAM, Fig. 3-4).

The two-year objectives for the high-speed acoustic communication project, using a High-Performance Acoustic Link (FAU-HPAL), are as follow:

1. Setup real-time signal processing software and hardware development and testing for the FAU-HPAL communication system (MillsCross).
2. Upgrade current FAU-GPAM software/hardware for optimal high and low-speed communication.
3. Run communication tests in conjunction with SFOMC Shallow Water MUX facility.

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14. ABSTRACT
Our long-term objective is a smart acoustic network for multiple underwater vehicle operation, with integrated communication and positioning capability. To do so, a new generation of Coherent Path Beamformer would act as a network decoder and arbitrator for data communication and long (short) base line. Also, wireless communication to shore would be available for control and real-time data transfer. Finally, the underwater vehicles will be carrying an improved version of the compact low-cost Acoustic Modem. This concept requires the network to be synchronous. The concept is to make the most efficient use of time and frequency band.

15. SUBJECT TERMS

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4. Achieve high-rate video and sonar data transmission from underwater vehicle during mission.

The two-year objectives for the high-reliability acoustic network using multiple General-Purpose Acoustic Modems (FAU-GPAM), with a monitoring option using the FAU-HPAL, are as follow:

1. Achieve reliable communication with the current FAU-GPAM generation in underwater vehicle conditions of operations (2000 meters max, mode 4 dual Viterbi/BCH or Reed-Solomon).

2. Design the third generation of FAU-GPAM with the following features:
   a) Smaller size and average power use, better multiple ADC/DAC, low electrical noise, Ethernet.
   b) New transducer with broader frequency band for multiple mode support.
   c) Multiple receivers for channel diversity.
   d) Greater processing power, improved multi-channel signal processing.

3. Monitor the underwater vehicle network using FAU-HPAL in FSK mode.

APPROACH

High-Speed Acoustic Communication using FAU-HPAL:

A high performance acoustic link called the FAU-HPAL has been developed, using a multi-element receiver array that provides 64 individual signals to a high-resolution analog-to-digital converter and digital storage system [1-8]. The source is the FAU General Purpose Acoustic Modem (FAU-GPAM) developed at FAU (sonar laboratory) and used for acoustic networking during underwater vehicle operation. The joint adaptive coherent path beamformer method consists in splitting the space and time processing into two separate sub-optimal processes. As a result, processing complexity is significantly reduced and the instabilities associated with large tap vectors at large time-frequency spread products are reduced. This method utilizes a different beamformer optimization strategy compared to the time domain optimization strategy, and allows to separately adjust the adaptation parameters for the spatial and temporal characteristics of the signal, which have vastly different requirements. The time domain signal is subject to variations in phase that require rapid filter updates whereas the directional characteristics of the signal do not vary appreciable over the message length and do not require a rapid adaptation response. This method allows for high-speed underwater acoustic communication in very shallow water using coherent modulation techniques, and offers a series of unique features: significant reduction of the signal-to-noise and interference ratio (SNIR), improvement of the bandwidth efficiency by reduction of the forward-error coding redundancy requirements and real-time evaluation of the time-spread by Doppler-spread product (BL).

Acoustic Network using multiple FAU-GPAM and FAU-HPAL Monitoring:

The FAU-GPAM is a high reliability shallow water acoustic modem developed for communication between underwater vehicle and general oceanographic use [9-12]. The modem uses 56 narrow band chirp FM pulses, each centered at a unique frequency located in the range of 16 kHz to 32 kHz. Data rates vary from 221 data bits per second to 1172 data bits per second, depending on the mode of transmission. Packets of information are synchronized using an adjustable number of chirp pulses in a known frequency hop pattern, followed by transmission format information and data. An “auto-baud” mode uses information garnered from previous transmissions for adaptation of the bit rate to the

acoustic environment. At the lowest rate, a four-time slot frequency hop pattern is used to provide maximum immunity to multipath interference. The modem is capable of using both half rate convolutional and BCH encoding in order to maximize error resilience. As a first step toward monitoring of the acoustic network using the FAU-HPAL, a multiple-channel signal-processing algorithm has been developed to decode frequency-hopped frequency-shift-keyed (FH-MFSK) FAU-GPAM signals acquired by the MillsCross receiver.

Synchronous Acoustic Communication and Navigation Buoys – FAU NavBuoys

The dual-purpose navigation/telemetry buoys provides navigation aid and tracking capabilities to AUVs. The acoustic navigation/telemetry design allows for accurate navigation without interfering with the regular acoustic communication mode. Most navigation systems require the transmitter to wait for an acoustic reply from the receiver(s) to calculate the message round-trip propagation time. The synchronous method uses synchronous transmitter(s) and receiver(s) technique using GPS and FAU-built timer cards. Transmitted navigation messages are time-stamped at the transmitter. The transmitted message is accurately synchronized at the receiver end to provide one-meter accuracy. When the message trigger is detected, the receiver reads current time the timer card, adds a known processing time delay to obtain the time of reception. Transmission time is deducted from reception time to get the time of flight. Since one way transmission is sufficient for navigation, navigation update rate is doubled and power consumption halved as compared with a standard navigation system. Also, the dual-purpose navigation/telemetry system combines communication and navigation hardware into a single unit on boats and inside AUVs. This reduces cost, power and size requirements for the embedded system, a highly desirable feature on Autonomous Underwater vehicle.

Dual-Purpose Acoustic Modem for Telemetry and Synchronous Navigation

The FAU-DPAM is a high reliability shallow water acoustic modem developed for communication between underwater vehicle and general oceanographic use. FAU-DPAM underwater acoustic modem is the second generation of modems developed at Florida Atlantic University. This new modem is being developed to meet current and future requirements in the underwater communications and underwater vehicle fields. The modem provides a robust communications system as well as a versatile platform for research and development of new underwater acoustics and communications techniques. The acoustic modem provides a wireless underwater communications link in the frequency band of 15 to 35 kHz. The host processor handles message traffic to and from the user, formats data to and from the digital signal processor (DSP), time tags incoming and outgoing messages and manages various system resources. The digital signal processor modulates/demodulates messages in the communication channel and manages channel access. The power amplifier drives a broadband communications transducer, while the low noise preamplifier conditions received signals for analog to digital conversion. External user RS232/RS422 serial and 10Base-T Ethernet interfaces are available for host processor communications. Additionally, the host processor address/data bus, host processor SPI serial bus, and DSP multi-channel buffered serial port are available to external devices. The host processor enables the user to easily reconfigure the modem for different communication needs while a powerful fixed point DSP (160 MIPS) allows the implementation of sophisticated encoding/decoding schemes.

Dual-Purpose Acoustic Modem in USBL Configuration

This USBL acoustic system is based on the Dual Purpose Acoustic Modem (DPAM) developed at Florida Atlantic University by Dr. Beaujean, and is currently installed on FAU-SQUID II (Figure 5). It currently uses a simple 27 kHz CW signal filtered in the frequency band using a Hilbert transform. The phase, which is a function of the angle of arrival, of the signal is computed for each transducer. Thus, using the three transducers, three estimations of the bearing angle can be made.

WORK COMPLETED (October 1st 2001 to September 30th 2002)

FAU Dual Purpose Acoustic Modem:

1) Assembly and trouble-shooting of 6 modem units: 3 canister-mounted units for boat usage, 3 embedded units for UUV and buoy purposes.

2) Testing of the units in communication mode, off the costs of Fort Lauderdale at ranges up to 3 km.

3) Demonstration (communication mode) during ONR Modem Fest 2001 in Gulf Port, Mississipi.

4) Development of a real-time Ultra-Short Baseline (USBL) real-time code to estimate the source location in real-time using the FAU-DPAM. This is a preliminary step toward an optimized real-time code allowing for combined inverted USBL and coherent demodulation of acoustic messages. This USBL code has been implemented and tested on the FAU-Squid II UUV (Dr. A. Leonessa).

High-Speed Acoustic Communication using FAU-HPAL:

1) Development of a more bandwidth-efficient PSK encoding technique based on raised-cosine pulse shaping and implementation of the code on the new FAU-DPAM. Presently, the FAU-DPAM can only be used as a source in PSK mode. At-sea tests are planned in early November 2002.

2) Implementation of an optimized C version of the joint adaptive coherent path beamformer processing technique for near real-time data processing of PSK sequences. This code is to be tested with at-sea data in early November 2002.

3) FAU-HPAL is ready for SFOMC operation, to be started in late January 2003.

Acoustic Network using multiple FAU-GPAM and FAU-HPAL Monitoring:

1) Development of a new adaptive demodulation technique using a reduced number of receivers. This technique is to be implemented on the 4-channel FAU-DPAM to improve the overall data rate and power consumption. The technique has been developed using data collected by the FAU-HPAL while monitoring two FAU-GPAM acoustic communication using boat platform off Fort Lauderdale, at a maximum range of 5 km.

2) Technical support to the Naval Postgraduate School and University of Lisbon: use of two FAU GPAM mounted on the Aries UUV and surface vehicle for oceanographic exploration in the Açores (Figure 2).

3) Installation and support of FAU-GPAM on the NATO FAU-OEX-C (Figure 4) for acoustic communications purposes (La Spezia, Italy).

Synchronous Acoustic Communication and Navigation Buoys – FAU NavBuoys

1) Deployment of 3 FAU-NavBuoys and FAU-HPAL in a turning basin (highly reverberent environment). The FAU-HPAL was used to record the FAU-NavBuoys transmissions.
2) Development of a new signal processing technique to decode synchronous communication and navigation messages, and estimate the location of the source using the FAU-HPAL.

RESULTS (October 1st 2001 to September 30th 2002)

FAU Dual Purpose Acoustic Modem:

1) Preliminary results during ONR Modem Fest 2001 in Gulf Port, Mississipi [16]:

Modem	Observed Range Rate (kbps·km)	Maximum Observed Rate (Kbps)	1-2km Track 1	3-4km Track 1	5-5.5km Track 1
FAU Modem	0.3	0.1			

Reliable Decoding, over 50% error free packets
Moderate Decoding, below 50% error free packets
No decoded packets, only detection

Note that the FAU-DPAM was demonstrated at an early stage of system testing. Details on the experiments are provided in the Modem-fest 2001 final report [16].

2) The Ultra-Short Baseline (USBL) navigation feature was successfully tested during trials at the AUVSi competition in August 2002. Preliminary test show a bearing accuracy of 1 degree, but more tests are needed to confirm this number.

High-Speed Acoustic Communication using FAU-HPAL:

1) Using this multiple-stage method, bit rates of 32000 bps can be achieved over 3000 meters range. Better reliability is expected with the new hardware at this rate.

2) Practical rates of 8000 bps to 16000 bps are achieved with high reliability using current hardware.

3) Experimental data collected half-mile off Port Everglades using FAU-HPAL and FAU-GPAM:

   a) up to 3.5km range, 20'to 40' water depth, Sand and Reef Bottom

   b) 0 to 3 knots source speed, Reverberation Time over 20 ms

4) Fast and slow fading properties of the channel are measured, as the BL product can vary by a decade in 116 ms, and by two decades within minutes, from 0.001 to 0.1. The real-time analysis shows a strong correlation between time spread, Doppler spread, spatial coherence of the acoustic channel and communication performance. The high-speed communications research also provides more scientific and experimental ground to understand the limitations of multi-channel adaptive receiver techniques in terms of stability, hardware requirements and channel tracking capability.

Acoustic Network using multiple FAU-GPAM and FAU-HPAL Monitoring:

A new multi-channel spatial diversity technique has been developed for underwater acoustic communications in very shallow waters [13-14]. This technique combines a novel synchronization method with maximum-likelihood symbol estimation. It was tested with a multi-channel Mills-Cross receiver using various numbers of elements. The FAU General Purpose Acoustic Modem source transmitted messages using 4 types of frequency-hopped multiple-frequency-chirp-keying (FH-MFSK) modulation: 4 hops at 221 coded bits per second (cps), 2 hops at 442cps, or no hopping at 1172cps. These types of modulation allowed for robust data transmission in adverse environment. The modem operated between 16 kHz and 32 kHz at 192dB of source level, at ranges from 1 to 5 km in 40 feet of water. Using only 4 channels of the Mills-Cross receiver array, messages coded at 1172cps were received with a Frame Error Rate (FER) of 0% at a range of 3 km. In the same 4-channel configuration, messages coded at 221cps were received with no frame error at 5 km. This reliable and computation-efficient method can be implemented on new generations of embedded acoustic modems, such as the 4-channel FAU acoustic modem, and can provide significant improvements in communication performance. See Figure 6 and 7 for more detailed results.

Synchronous Acoustic Communication and Navigation Buoys – FAU NavBuoys

The goal of this research is to investigate the potential of the acoustic Millscross communication system for underwater navigation [15]. In this study, the coherent path beamforming and digital communication decoding processes were modified to incorporate the navigation function. Modifications included adding a Direction of Arrival (DOA) algorithm to the Coherent Path Beamforming (CPB) protocol, and adding a Viterbi decoding algorithm to correct and reject transmission errors. Finally, two different navigation modes were developed. The user mode enables evaluation of the position and spatial orientation of the fixed receiver by triangulation, while the task of the tracking mode is to determine the varying position of the emitters. During the experiment in the intracoastal, errors exceeding 25 error- bits occurred for 45% of messages. Adding a 2.1 kHz band symbol to the packet strips, which contain 76 300-Hz-wide symbols, provided an improvement on the estimation accuracy of the direction of arrival. The coherent path beamforming method applied on this wide band symbol specially devoted to the navigation message, gives impressive results considering the environment studied. The beamformer is able to steer towards the source with good accuracy. The resulting error with this method went from 30% to under 15 % of the expected angle of DOA in worst-case conditions. By worst-case conditions, it is meant that the reverberation level coefficient was up to –3dB of the peak signal energy level, while the signal to ambient noise SNR was as low as 20dB. Therefore the system allows a good estimation of the target position in most circumstances. The tracking mode function stores the position of the sources. The position accuracy of the sources depends on the GPS/DGPS precision. GPS data collected during the experiment showed that DGPS accuracy was 1 to 2 meters and GPS accuracy was 4 to 5 meters. The user-mode, developed for the receiver position estimation, works satisfactorily. The directionality of the target with respect to the

modems is determined within 5% to 15% accuracy, while the position is known within 5 meters. See Figure 8 and 9 for more detailed results.

IMPACT/APPLICATIONS

Experimental results are providing a new insight to the understanding of how shallow water propagation conditions affect the information capacity of digital data transmission for sonar operating in the frequency range of 25 kHz. Millions of data bits encoded using PSK and FSK have been transmitted at distances exceeding five kilometers over a moving platform. Error rates, adaptation time constants, and the influence of the environment on the stability of the various modes of propagation are inferred. Principal component analysis of the received data using moving platforms has also provided an important insight into the frequency smear of each of the various multipath receptions. This information is invaluable in generating models for use in testing acoustic modem designs and high-rate data transmission in shallow water environment. The MFSK modem proves that use of multiple frequency channels and frequency-hoping technique are suited for multiple-users underwater communication. Finally, the acoustic navigation/telemetry buoy design allows for accurate navigation without interfering with the regular acoustic communication mode. The fusion of these three techniques (FAU-HPAL, FAU-GPAM and FAU-DPAM) is the next step for a fast and reliable underwater acoustic network.

TRANSITIONS

The current generation low-cost single channel modem that uses Gaussian spread spectrum wavelets with compensation and the associated hardware has been successfully transitioned to a commercial oceangraphic instrumentation company: Edgetech Inc. has manufacturned the single-channel modems (GPAM). The new generation of dual purpose acoustic modem has been disclosed to FAU and currently following a very similar path.

RELATED PROJECTS

The Smart Acoustic Network project has three important objectives: high-speed acoustic communication, high-reliability acoustic networking and combined navigation/telemetry. This lead us to develop tools for obtaining a better understanding of the underwater acoustic channel in shallow water. Success in these objectives will be extremely beneficial to other projects in the ONR AOSN effort as well as other Navy objectives in shallow water acoustics.

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EXTRA REFERENCE

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Figure 1. FAU High-Performance Acoustic Link (FAU-HPAL or "MillsCross")

Figure 2. General Purpose Acoustic Modem (GPAM) and Aries UUV Platform

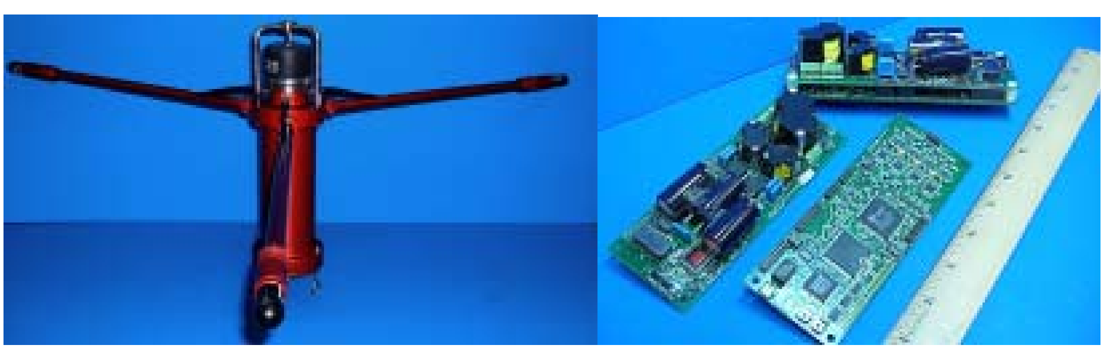

Figure 3. Dual Purpose Acoustic Modem (DPAM) and Embedded Electronics

Figure 4. General Purpose Acoustic Modem (GPAM) and NATO OEX-C UUV Platform

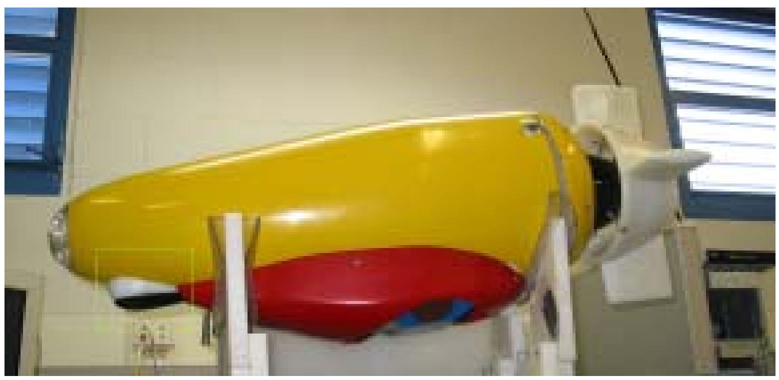

Figure 5. Dual Purpose Acoustic Modem (DPAM) in USBL Configuration mounted on FAU-Squid II

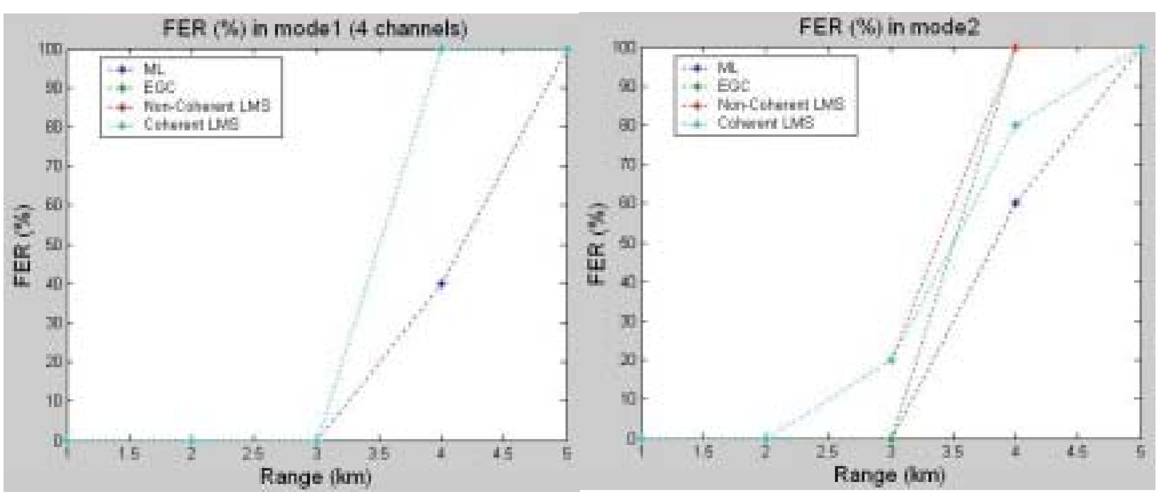

Figure 6. Monitoring of FAU-GPAM communications using only 4 channels of the FAU-HPAL (Mode 1 - 1172 cps, Mode 2 – 880 cps)

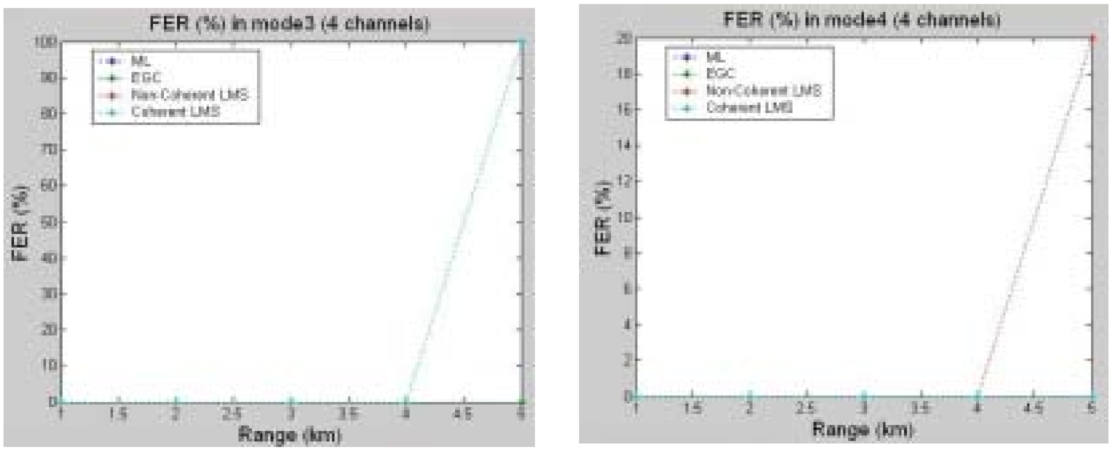

Figure 7. Monitoring of FAU-GPAM communications using only 4 channels of the FAU-HPAL (Mode 3 - 440 cps, Mode 2 – 220 cps)

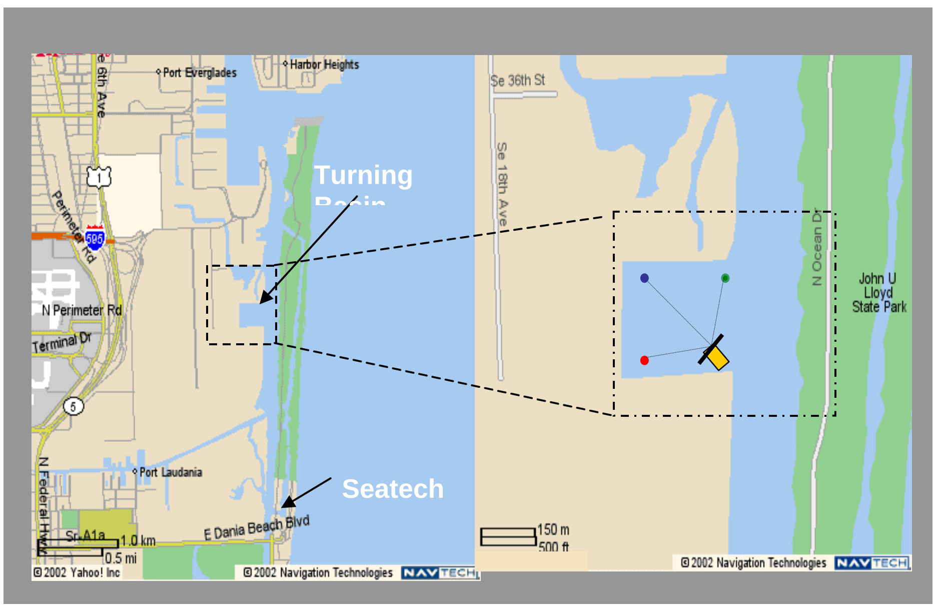

Figure 8. Tracking of FAU-NavBuoys using 64-channel FAU-HPAL – Experiment Description

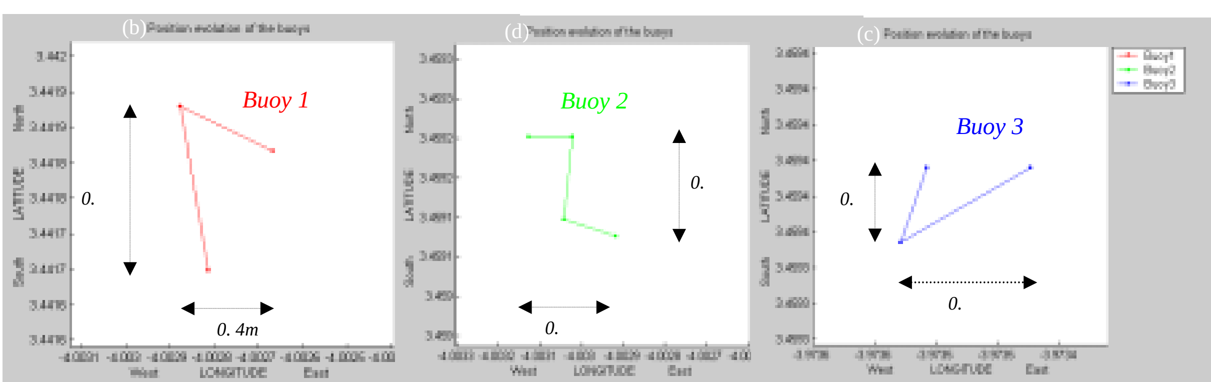

Figure 9. Tracking of FAU-NavBuoys using 64-channel FAU-HPAL – Results